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A new device to remotely measure heat flux and skin temperature from free-swimming dolphins

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Abstract

To enhance our understanding of how aquatic endotherms respond thermally to their environment, we present two new designs for recording heat flux (HF) and skin temperature (T_s) from the dorsal fins of free-ranging dolphins. The first package, held on by a series of small suction cups, was designed for short-term deployments on the order of hours. The second package, a long-term attachment, was held on via two 5.0-mm -Delrin® pins and was designed for deployments on the order of days. The former version was configured to release remotely, by way of a galvanic linkage, removing the need to re-capture tagged dolphins. The latter was designed to be removed after re-capture of the individual but also included a fail–safe galvanic release. One of the major advances of our approach is that it allows both convective and conductive pathways of heat loss to be dynamically recorded from free-swimming wild dolphins, whereas previous approaches have recorded primarily conductive heat loss from trained captive or restrained wild dolphins. The short-term, re-usable package has been field-tested on 55 bottlenose dolphins (*Tursiops truncatus*) in Sarasota Bay, Florida and the long-term device on two spotted dolphins (*Stenella attenuata*) in the eastern tropical Pacific Ocean. By also incorporating into each package a time–depth–velocity recorder we were able to examine patterns of heat flux in relation to changing behavioural states of the tagged individual. Heat flux recorded at the dorsal fin was found to be individually variable and dynamic. Water temperature (T_w) had a profound effect on patterns of heat loss in both species with HF increasing with even minor decreases in T_w. This device significantly improves our ability to understand the thermal biology of dolphins as they move about in their natural environment.

Keywords: Dolphin; Free-swimming; Heat flux; Skin temperature; Thermal data logger; Water temperature

1. Introduction

All animals respond thermally to the environment in which they live (reviewed in McNab, 2002). Aquatic endotherms, in particular, face considerable challenges as heat is conducted away from their bodies at a rate minimally 25 times greater than it would be in air

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(Schmidt-Nielsen, 1997). Cetaceans (whales, dolphins and porpoises) have garnered special attention as they live exclusively in an aquatic habitat and are unable to utilize traditional mammalian thermoregulatory mechanisms such as panting, sweating or behaviourally changing the ratio of relative surface area to volume. Cetaceans have therefore evolved many specialized thermoregulatory adaptations (see Pabst et al., 1999 for review) including: countercurrent heat exchangers (Scholander and Schevill, 1955; Rommel et al., 1992, 1993, 1994; Elsner, 1999), thick insulative layers of blubber (Parry, 1949; Doidge, 1990; Worthy and Edwards, 1990; Koopman, 1998; Dunkin et al., 2005), coordination between thermoregulation and the dive response (Noren et al., 1999; Williams et al., 1999), and various adaptations in the appendages and blubber that allow excess heat to be dissipated by redirecting blood flow (Scholander and Schevill, 1955; McGinnis et al., 1972; Noren et al., 1999; Williams et al., 1999; Meagher et al., 2002). Together these various adaptations have allowed cetaceans to successfully occupy far differing thermal habitats, from tropical to arctic waters (Reeves et al., 2002).

Heat loss in mammals occurs via conductive, convective, evaporative, and radiative pathways (reviewed in Elsner, 1999). In cetaceans, conductive and convective pathways are considered the most important (e.g., McNab, 2002). To date, studies that have investigated heat loss in dolphins have been conducted on captive or temporarily restrained wild animals (Hampton et al., 1971; Hampton and Whittow 1976; McGinnis et al., 1972; Heath and Ridgway, 1999; Noren et al., 1999; Williams et al., 1999; Meagher et al., 2002). Two biases introduced when conducting thermal experiments on either stationed captive or temporarily restrained wild dolphins are: (a) convective effects of cooling (via the bulk flow of water across the animal) are artificially reduced and (b) other environmental/behavioural conditions are usually held relatively constant (water temperature, depth, foraging activity etc.). These previous studies have therefore presented important data on conductive heat loss under static conditions, but patterns of heat loss have not yet been investigated in cetaceans as they actively swim and dive. Recently, a new device was introduced that allowed heat flux to be measured from free-swimming pinnipeds (Willis and Horning, 2005). These authors reported successful test results from both captive and wild individuals. This device is not suitable for use on cetaceans because it was designed to be attached with glue to the seal's fur.

Heat loss, incorporating both conductive and convective effects under dynamic conditions, has not been reported from a free-swimming cetacean. We therefore developed a small thermal data logger package that could record heat flux and skin temperatures from free-swimming dolphins. This device was used in conjunction with commercially available time–depth–velocity recorders to provide further information on diving behaviour and water temperature. This technological development was carried out in response to the need to record thermoregulatory behaviour of spotted dolphins (*Stenella attenuata*) in the eastern tropical Pacific Ocean (ETP). It has been hypothesized that dolphins that are chased during tuna fishing operations (National Research Council, 1992) have the potential to become stressed thermally to a point that could potentially be impeding population recovery (Forney et al., 2002; Gerrodette and Forcada, 2005). The logger was also used extensively to study patterns of heat loss in wild bottlenose dolphins (*Tursiops truncatus*) in Sarasota Bay, Florida.

Here we present two versions of this new thermal data logger for odontocetes. The first, designed for multiple, short deployments on bottlenose dolphins, was attached by suction cups. The second version was designed for single, longer deployments on spotted dolphins and was secured surgically via two 5-mm Delrin® pins. Each package has undergone field deployments and representative data from these experiments will be highlighted in addition to the technical details of each design.

2. Materials and methods

2.1. The thermal data logger

We developed two versions of the thermal data logger: a short-term and a long-term design (Fig. 1). Both consisted of a custom-made plastic saddle called a Trac-Pac® (Trac-Pac Inc. Fort Walton Beach, FL, Patent number 6,023,919) that was attached to the dorsal fin (Shippee et al., 1995; Davis et al., 1996; Nowacek et al., 1998). The saddle had compartments that housed the electronics for measuring and recording heat flux (HF) and skin temperature (T_s), as well as a time–depth recorder that recorded water temperature (T_w), depth (D) and velocity (V), and a small VHF radio to facilitate tracking of the tagged animals and recovery of jettisoned packs.

2.1.1. Short-term package

This version was constructed using a 3.5-mm modified polyethylene that was designed to fit the dorsal fin of a mature bottlenose dolphin (Fig. 1). The saddle was lined with open-cell foam (3.5 mm) to which was glued a series of small suction cups (Rubbermaid, Fairlawn, Ohio). The suction cups adhered to the dorsal fin and held the saddle in place.

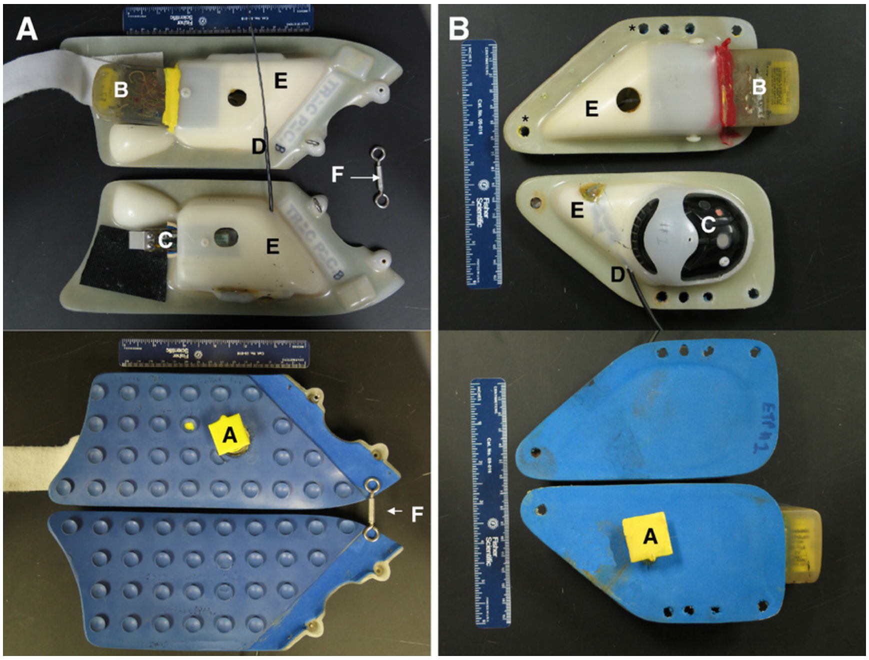

Fig. 1. Both versions of the heat flux and skin temperature data logger. (A) Shows the short-term device which was attached to the fin via a series of small suction cups. The saddle conformed around both sides of the dorsal fin, joining at the front by way of galvanic pins and at the rear by a Velcro® strap. (B) Shows the long-term package that was attached via two 5-mm Delrin® pins that were located at the holes marked *. Since this saddle extended past the trailing edge of the dorsal fin the rear pin holes were tightened together using a plastic tie wrap. The additional holes were included to allow optimal pin placement on different sized dorsal fins. A = heat flux disk, B = HF amplifier and data logger, C = time–depth recorder, D = VHF antenna, E = floatation, F = Mg linkage. Scale shown = 15 cm.

The suction cups also raised the saddle up from the skin and allowed water flow over this appendage. A 2.5-cm-wide Velcro® strap went around the caudal margin of the dorsal fin, connecting the right and left sides of the saddle. The Velcro® strap permitted adjustable tightening of the package and held it securely in place. Magnesium (Mg) linkages (International Fishing Devices, Pompano Beach, FL) secured the front sides of the package together and could be adjusted by turning set screws that threaded into the Mg. Galvanic action between the steel set screws and the Mg caused the latter to corrode in seawater, which allowed the two halves of the saddle to separate and detach from the dolphin (Fig. 1). Different sized Mg linkages were calibrated to release after specific times, depending upon water temperature.

2.1.2. Long-term package

This version was also constructed out of 3.5 mm modified polyethylene (Fig. 1). It was moulded to fit a mature spotted dolphin dorsal fin. The saddle was lined with 3.5 mm open-cell foam. Rather than using suction cups, this package was held in place using two 5-mm Delrin® pins that were piloted through holes that had been surgically cut through the dorsal fin using a sterilized stainless steel coring tool (Irvine et al., 1982; Scott et al., 1990; Westgate et al., 1995; Read and Westgate, 1997; Lander et al., 2001; Norman et al., 2004). Pins, the coring tools as well as the dorsal fin were cleaned using a topical antiseptic solution prior to attachment. The rear holes of the package (Fig. 1) were tightened together using a tie wrap since the package extended beyond the trailing edge of the dorsal fin. The saddle was raised off the surface of the dorsal fin (to minimize insulation effects and allow water flow) by inserting 2.0 cm diameter foam washers on the pins between the skin and saddle. Two washers were used on each pin which provided approximately 6 mm of separation. For our purposes, this package was designed to be removed during a planned re-capture of the tagged dolphins. To ensure that the tag would be released even in the event that re-capture was not possible, small Mg nuts backed by stainless steel washers were threaded on the ends of the Delrin® pins. Galvanic action between the two dissimilar metals would cause the Mg to corrode, thereby eventually releasing the package from the animal.

2.1.3. Data collection

Both thermal data logger packages were developed to record HF and T_S from wild dolphins. The HF transducer (Vatell Episensor B02, Vatell Corp.

Christensburg, VA) produced a weak signal (1–100 μV) at frequencies from DC out to about 1000 Hz. Therefore to effectively record heat flux we designed a small, low-power, high-gain amplifier that would amplify the low-signal of the HF disks so it could be read by a commercial data logger (0–2.5 V) (Fig. 2). The circuit was constructed using surface mount, high-tolerance components (1%) and low-temperature-coefficient resistors to minimize internal errors. It had a finished size of 55 × 40 × 5 mm. To achieve the necessary gain requirement (12 000 times), we utilized a cascade design using two amplifiers. The first, an instrument amplifier (INA 128 Burr Brown, Tucson, AZ), had a gain of 1250 times. This signal was then further amplified by 10 times using a low-power op amplifier (AD822 Analog devices, Norwood, MA) (see Fig. 2). These voltages were recorded using a modified HOBO (Onset Computer Corp., Pocasset, MA) 4-channel data logger, which had an adjustable sampling rate (0.5 s–9 h) and an internal resolution of 10 mV. The HF amplifier and HOBO data logger were encased in Scotchcast #5 electrical resin (3M, Austin, TX) and had a final potted size of 90 × 45 × 20 mm.

Skin temperatures were recorded using two methods. The first, used on the long-term packages, relied on a copper–constantan thermocouple (TT-T-30-SLE, Omega Engineering, Stamford, CT) mounted on the surface of the HF disk. Skin temperatures were recorded by a HOBO T-type thermocouple data logger (Onset Computer Corp., Pocasset, MA) that was potted with the HF amplification circuit and HOBO 4-channel logger. The HOBO T-type had a resolution of 0.4 °C. The second method, incorporated into the short-term design, used an NTC thermistor (Thermonetics type MC65, Edison, NJ) which was also mounted directly onto the surface of the heat flux disk. Temperatures were recorded as voltages to the HOBO 4-channel via a simple circuit that was included in the amplifier design (Fig. 2). The whole unit was powered by a single, regulated 3 V lithium battery (Panasonic BR-2/3A, Elgin, IL). The entire package drew approximately 8 mA which gave the data logger a life expectancy of about 150 h. Typically, batteries were replaced every 100 h by first cutting away the surrounding epoxy resin, replacing the cell and repotting to its original size.

The combination of the low-noise amplifier and the sensitivity of the Episensor HF transducer meant that HF readings as low as 1.04 W/m^2 could be detected. Due to the limitations imposed by the internal resolution of the HOBO 4-channel data logger (10 mV), however, the minimum recordable change in HF was 5.0 W/m^2. Heat flux reading as high as 1250 W/m^2 (i.e., 2.5 V) could theoretically be recorded. The lowest and highest reading that could be obtained from each logger varied depending upon the internal calibration of each HF transducer which varied between 750 and 1950 W/m^2 per mV. Similarly, changes in skin temperatures as low as 0.1 °C could be detected by the NTC thermistors, but the 10 mV data logger resolution limited this to recordable changes of 0.35 °C. The skin thermistors had a theoretical range of −32 to 63 °C.

2.1.4. Tag design details

The plastic of each saddle was moulded around two hydrodynamically shaped syntactic foam (Emerson and Cuming, Canton, MA) blocks (approx. 105 × 70 × 25 mm) that provided the floatation for the package (Fig. 1). These blocks were configured with pockets on each side of the saddle to accommodate the electronic packages. In addition, small lead ballast weights were added to the short-term packages to ensure that the VHF antenna was oriented vertically and out of the water when the package had been released and was free-floating. We did not attach the ballast to the long-term packages since they were manually removed from the animals. On the right side of the saddle we attached the VHF radio transmitter (148 MHz) (Holohil, Carp, ON; Telonics Mesa, AZ) and a time–depth–velocity recorder (TDR) (either Mk.7, Mk. 8, or Mk. 9, Wildlife Computers, Woodenville, WA). The VHF transmitters allowed us to radio-track the animals throughout each deployment and to recover the packages via animal re-capture or after they had been shed. The TDR allowed us to record dive D (±0.25–0.5 m), T_w (±0.05–0.1 °C) and relative V (±0.02 m/s). On the left side we attached the HF electronics package. The HF transducer (2.5 × 2.5 cm) was waterproofed with a rubberized coating (Plastidip, PDI Inc., Circle Pines, MN) and attached to a short spring that pushed the disk up gently against the dorsal fin when the saddle was in place. A short waterproof wire (5 cm) connected the disk to the electronics package. A 1.5-cm hole was drilled through the saddle where the spring was attached which allowed the water to freely flow to the back of the disk. The relative position of the heat flux disk on each dorsal fin was different because of individual variation in dorsal fin size and shape but generally the heat flux was collected near the middle of the dorsal fin.

2.1.5. Calibration

The temperature recorders of each thermal package (skin thermocouples and thermistors and time–depth–velocity recorders) were tested and calibrated before and after each deployment in a water bath (RE-120 Lauda Ecoline, Brinkmann Instruments, Inc.,

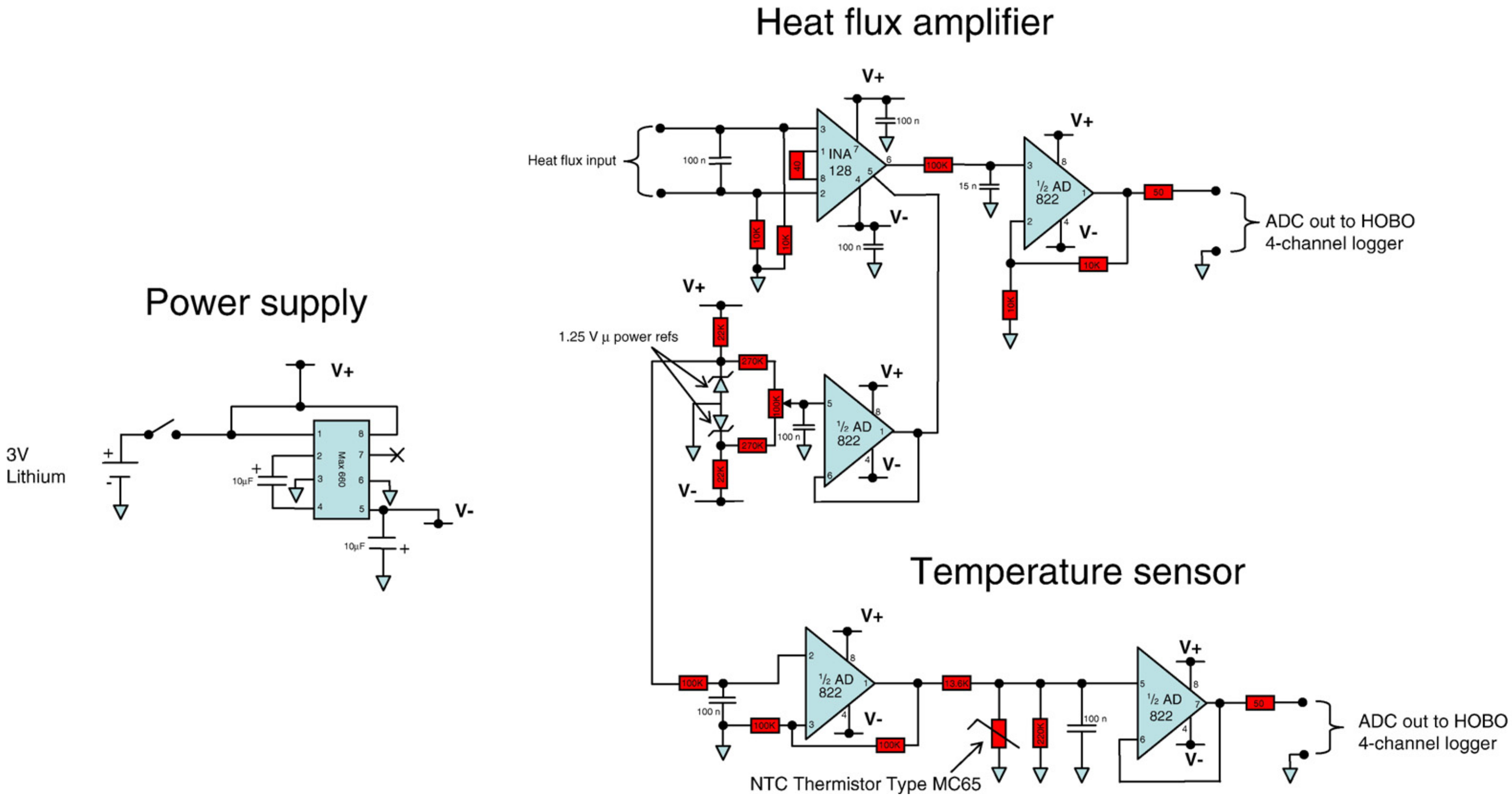

Fig. 2. Circuit diagram for the heat flux amplifier and skin temperature sensor. Resistor and capacitor values are shown. Pin numbers for instrument (INA128) and operation amps (AD822) are also indicated. Circuit was powered by a 3 V lithium cell that was run through a voltage inverter (Maxim 660, Sunnyvale CA) and was regulated (±1.25 V).

Westbury, NY) over the range of temperatures (15–35 °C) that could be encountered during the experiment. Heat flux disks were calibrated by the manufacturer (Vatell Corp., Christensburg, VA) and rather than being re-calibrated were regularly replaced (on average after four deployments).

2.2. Deployments

Prior to deployment of the short-term thermal logger package in the field, it was trial tested during May 1999 on two captive male bottlenose dolphins maintained at the Long Marine Lab at the University of California at Santa Cruz (UCSC). Due to husbandry concerns, we chose not to test the long-term version of the thermal logger on captive dolphins.

2.2.1. Short-term deployments

Thermal data were collected from bottlenose dolphins temporarily captured and restrained in the waters of Sarasota Bay, Florida during health assessment operations in June 1999–2005 (Wells et al., 2004). These capture methods have been described in detail elsewhere (Wells et al., 1987; Wells, 1991). Briefly, a 500 m × 4 m net was deployed around small groups of dolphins in shallow water. Dolphins were restrained, placed on a stretcher and moved to a shaded foam pad on a nearby veterinary examination boat. Here dolphins underwent a variety of health and biological assessments. Before release, selected individuals were fitted with the thermal data logger package (Fig. 3). With the exception of animals < 2 years, individuals encompassed a wide range of age and sex classes.

Throughout each deployment, dolphins were radio-tracked from a 5 m boat at distances ranging from 10–500 m. During each focal follow, behavioural data were recorded every 30 min along with the animal's position and water depth. The time of each ventilation event was recorded throughout the duration of the track. Once the buoyant package was released from the dolphin's dorsal fin, it was recovered and the data downloaded to a personal computer using specialized software from Onset (HOBO Boxcar Pro 4.0) and Wildlife Computers (Instrument Helper 1.005).

2.2.2. Long-term deployments

Thermal data were collected from spotted dolphins captured as part of the Chase and Encirclement Stress Studies (CHESS) research cruise that was carried out in the ETP by the National Marine Fisheries Service during August and September of 2001 (Forney et al., 2002).

Fig. 3. The short-term thermal logger attached to the dorsal fin of an adult bottlenose dolphin in Sarasota Bay, FL.

Animals were captured by a commercial tuna purse seiner contracted for this study, temporarily restrained in flooded 2-m rubber rafts and subjected to a variety of health and biological assessments before being fitted with the thermal data logger and released. Animals were radio-tracked from the bridge of the 54 m NOAA R/V *McArthur* throughout each deployment. When the animals were re-captured 1–4 days post-release, the tags were removed, and the data downloaded to a personal computer using the same software as in the short-term deployments.

3. Results

3.1. Initial testing

The trials at Long Marine Lab revealed that it was possible to collect both HF and T_s data from swimming and diving dolphins in a pool setting. Although the behaviour of these dolphins precluded any long-term deployments (most lasted only a few minutes before the packs were shaken off), the design worked well and did not cause any obvious tissue response to the dorsal fin. Based on these preliminary results we believed the design was suitable for further testing in the field.

3.1.1. Short-term deployments

From June 1999 through June 2005, the thermal logger was deployed 55 times on bottlenose dolphins. Deployments ranged in duration from only a few seconds to over 23 h (Table 1, Fig. 4). All deployed packages were recovered, even when weather conditions precluded continuous tracking. Depending on the nature of the deployment, sampling rates were adjusted to between 2 and 4 s. By taking two samples every 2 s (one for T_s and one for HF) the logger, which had a total memory capacity of 32 K, had the potential to collect data for 9 h. Of the 37 longer deployments (over 30 min), 34 had good records of HF, T_w, T_s and D. In

Table 1
Biological data from thermal data logger deployments on wild dolphins between 1999 through 2005

Date	Species	Sex	Length	Age class	Duration	HF	T_s	T_w	D	V
Jun-10-99	Tt	F	261	Adult	0:30	Yes	Yes	Yes	Yes	NA
Jun-10-99	Tt	F	239	Subadult	4:08	Yes	Yes	Yes	Yes	NA
Jun-11-99	Tt	F	253	Adult	0:36	Yes	Yes	Yes	Yes	NA
Jun-14-99	Tt	M	277	Adult	7:24	Yes	Yes	Yes	Yes	NA
Jun-15-99	Tt	M	278	Adult	1:11	Yes	Yes	Yes	Yes	NA
Jun-15-00	Tt	M	270	Adult	5:42	No	Yes	Yes	Yes	NA
Jun-16-00	Tt	F	239	Subadult	1:25	No	No	No	No	NA
Jun-20-00	Tt	M	267	Adult	2:46	Yes	Yes	Yes	Yes	NA
Jun-21-00	Tt	F	NA	Adult	2:59	Yes	Yes	Yes	Yes	NA
Jun-22-00	Tt	F	237	Subadult	7:58	Yes	Yes	Yes	Yes	NA
Jun-23-00	Tt	F	252	Adult	0:12	Yes	Yes	Yes	Yes	NA
Jun-23-00	Tt	M	252	Adult	2:44	Yes	Yes	Yes	Yes	NA
Jun-04-01	Tt	M	261	Adult	0:01	Yes	Yes	Yes	Yes	NA
Jun-05-01	Tt	F	242	Adult	2:47	Yes	Yes	Yes	No	NA
Jun-07-01	Tt	M	236	Subadult	0:05	Yes	Yes	Yes	No	NA
Jun-07-01	Tt	F	240	Adult	1:55	Yes	No	Yes	No	NA
Jun-08-01	Tt	M	257	Adult	1:16	No	No	Yes	Yes	Yes
Jun-08-01	Tt	F	217	Subadult	0:11	Yes	Yes	Yes	Yes	Yes
Jun-11-01	Tt	F	259	Adult	7:52	Yes	Yes	Yes	Yes	Yes
Jun-12-01	Tt	F	244	Adult	0:01	Yes	Yes	Yes	Yes	Yes
Sep-19-01	Sa	M	190	Adult	23:00	Yes	Yes	No	No	No
Sep-22-01	Sa	M	204	Adult	84:00	Yes	Yes	Yes	Yes	Yes
Jun-03-02	Tt	F	248	Adult	1:02	Yes	Yes	Yes	Yes	Yes
Jun-03-02	Tt	F	265	Adult	0:16	Yes	Yes	Yes	Yes	Yes
Jun-04-02	Tt	F	250	Adult	0:01	Yes	Yes	Yes	Yes	Yes
Jun-04-02	Tt	F	241	Adult	0:51	Yes	Yes	Yes	Yes	Yes
Jun-05-02	Tt	F	229	Adult	0:01	Yes	Yes	Yes	Yes	Yes
Jun-05-02	Tt	M	223	Subadult	1:09	Yes	Yes	Yes	Yes	Yes
Jun-06-02	Tt	F	250	Adult	0:56	Yes	Yes	Yes	Yes	Yes
Jun-06-02	Tt	M	237	Subadult	3:29	Yes	Yes	Yes	Yes	Yes
Nov-5-02	Tt	M	?	Calf	1:24	Yes	Yes	Yes	Yes	Yes
Feb-04-03	Tt	M	202	Calf	0:19	Yes	Yes	Yes	Yes	Yes
Jun-02-03	Tt	M	213	Subadult	0:02	Yes	Yes	Yes	Yes	Yes
Jun-05-03	Tt	F	210	Calf	1:10	Yes	Yes	Yes	Yes	Yes
Jun-06-03	Tt	M	250	Adult	0:21	Yes	Yes	Yes	Yes	Yes
Jun-06-03	Tt	F	245	Subadult	1:03	Yes	Yes	Yes	Yes	Yes
Jun-09-03	Tt	F	249	Adult	0:00	Yes	Yes	Yes	Yes	Yes
Jun-09-03	Tt	M	242	Adult	0:03	Yes	Yes	Yes	Yes	Yes
Jun-10-03	Tt	M	238	Adult	1:33	Yes	Yes	Yes	Yes	Yes
Jun-10-03	Tt	M	233	Subadult	0:38	Yes	Yes	Yes	Yes	Yes
Feb-02-04	Tt	F	243	Adult	0:01	Yes	Yes	Yes	Yes	No
Feb-02-04	Tt	M	224	Adult	1:41	Yes	Yes	Yes	Yes	No
Feb-03-04	Tt	F	252	Adult	1:01	Yes	Yes	Yes	Yes	No
Feb-03-04	Tt	F	248	Adult	0:20	Yes	Yes	Yes	Yes	No
Feb-04-04	Tt	F	244	Subadult	4:01	Yes	Yes	Yes	Yes	No
Feb-09-04	Tt	M	235	Adult	0:30	Yes	Yes	Yes	Yes	No
Feb-09-04	Tt	F	269	Adult	0:00	Yes	Yes	Yes	Yes	No
Feb-10-04	Tt	M	244	Adult	0:34	Yes	Yes	Yes	Yes	No
Feb-10-04	Tt	F	259	Adult	0:01	Yes	Yes	Yes	Yes	No
Jun-03-04	Tt	M	246	Adult	0:01	Yes	Yes	Yes	Yes	No
Jun-04-04	Tt	M	258	Adult	1:33	Yes	Yes	Yes	Yes	No
Jun-04-04	Tt	M	243	Subadult	0:46	Yes	Yes	Yes	Yes	No

(continued on next page)

Table 1 (*continued*)

Date	Species	Sex	Length	Age class	Duration	HF	T_s	T_w	D	V
Jun-07-04	Tt	M	217	Subadult	23:02	Yes	Yes	Yes	Yes	No
Jun-10-04	Tt	F	215	Adult	7:11	Yes	Yes	Yes	Yes	No
Jun-11-04	Tt	F	234	Subadult	1:26	Yes	Yes	Yes	Yes	No
Jan-31-05	Tt	M	216	Subadult	20:00	Yes	Yes	Yes	Yes	No
Jun-07-05	Tt	M	247	Subadult	5:32	Yes	Yes	Yes	Yes	No

All bottlenose dolphin deployments took place in Sarasota Bay, Florida, USA, those on spotted dolphins (in bold) took place in the ETP. HF = heat flux, T_s = skin temp, T_w = water temp, D = depth, V = velocity.

addition, 11 records of V were also obtained. Example records are shown in Figs. 5 and 6. Early on in the experiment the thermal package often fell off before the Mg pins corroded and broke, but as we became more familiar with the behaviour of the suction cups we were able to achieve longer deployments that could be timed according to the thickness of the Mg linkages (Fig. 4).

3.1.2. Long-term deployments

We successfully deployed the thermal logger on two mature spotted dolphins in the ETP (Table 1, Fig. 4). Owing to the nature of the experiment, these packages were required to remain on the dolphins for longer periods of time (up to 4 days) and hence required a more secure attachment method. As we wanted the packages to collect data throughout the deployment, we set the sampling intervals to 6 or 8 s. Since both the HF and T_s HOBO (Onset, MA) loggers had their own internal memories (32K), the device had the potential to collect data for between 2.5 and 3 days, respectively. The first deployment was designed to last 2 days but was cut short after 1 day because of deteriorating weather conditions. During this 23-hour deployment the TDR became dislodged and was lost. The package did collect HF and T_s data. The second deployment lasted 3 days. Prior to deployment we had made a small

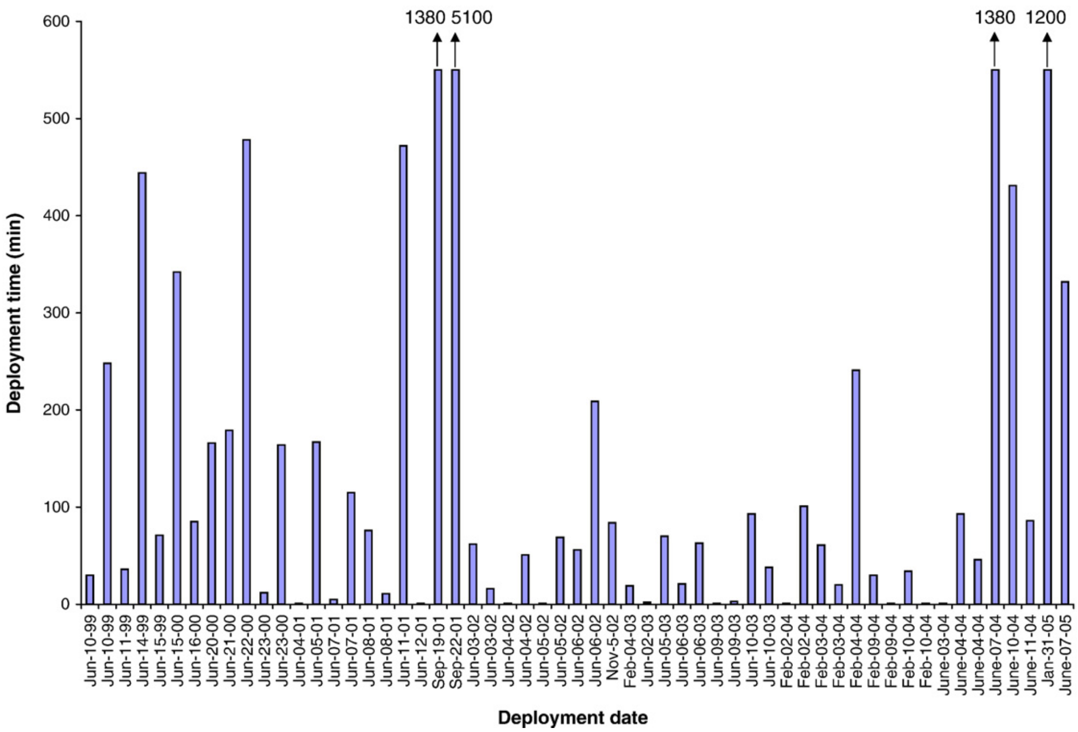

Fig. 4. Length of deployments (min) of the thermal logger on bottlenose and spotted dolphins during 1999 through 2005. Longer deployments extend off the scale of this graph and actual times are indicated. All deployments <1 min are indicated as being 1 min long.

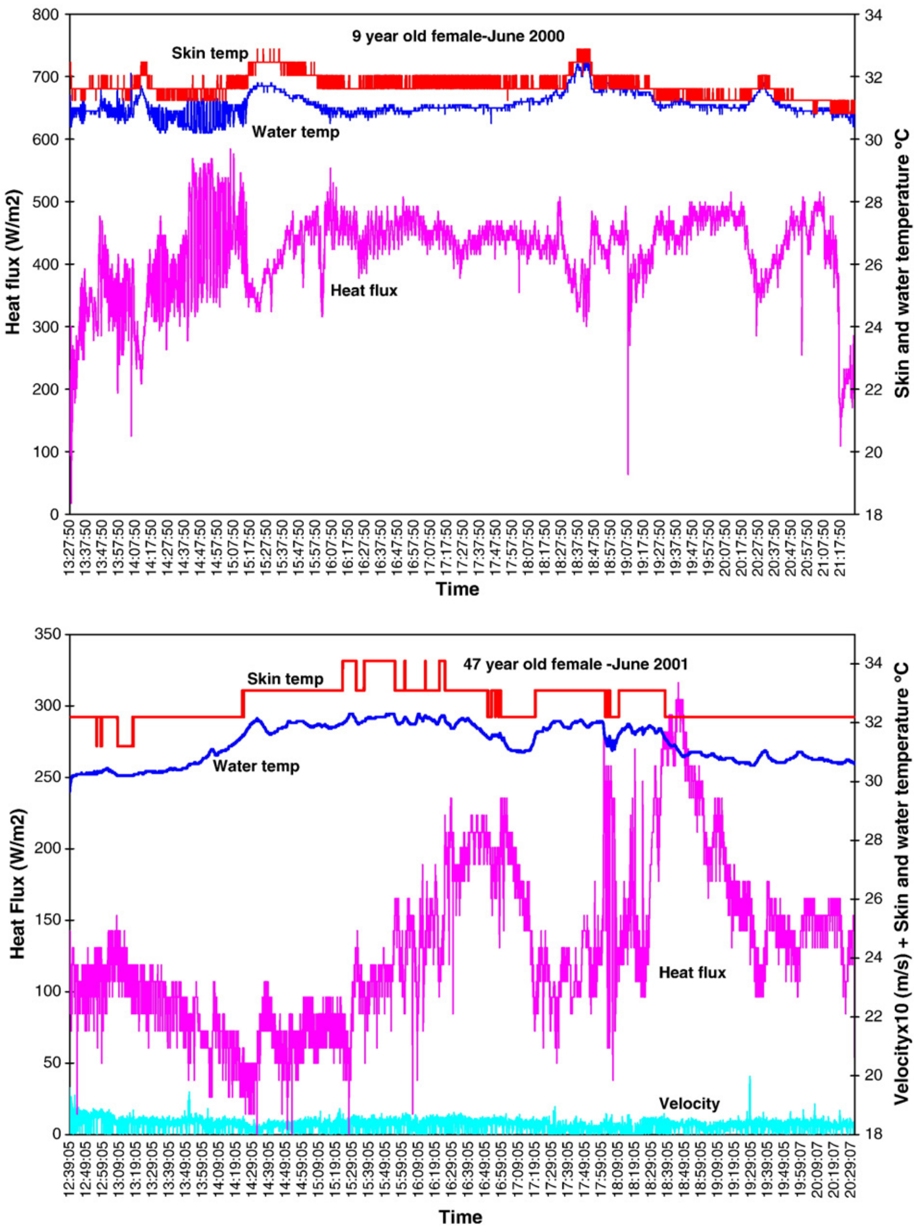

Fig. 5. Two representative data records obtained from bottlenose dolphins in Sarasota Bay FL. The top figure shows heat flux (HF), skin and water temperature (T_w) records that were obtained over 7.5 h from a 9-year old female in June 2000. Notice that around 14:40, HF becomes much more variable, going through rapid oscillations as T_w changes. The bottom half of the figure shows a 7.5 h trace from a 47-year old female. This dolphin's HF is changing on the period of hours despite the relatively constant swimming velocity and water temperatures.

modification to the saddle to prevent TDR loss and this deployment collected records of HF, T_s, T_w, and V. A portion of this data record is shown in Fig. 7.

4. Discussion

Previous investigations of heat loss in dolphins have relied on obtaining data from captive or restrained animals. This study demonstrates that it is possible to collect HF and T_s from free-swimming wild dolphins. The configurations presented here allowed the data to be continuously collected for periods of hours to days. When used in conjunction with commercially available time–depth–velocity recorders, heat loss results can be analysed in relation to dynamic activity states and changing swimming and diving patterns.

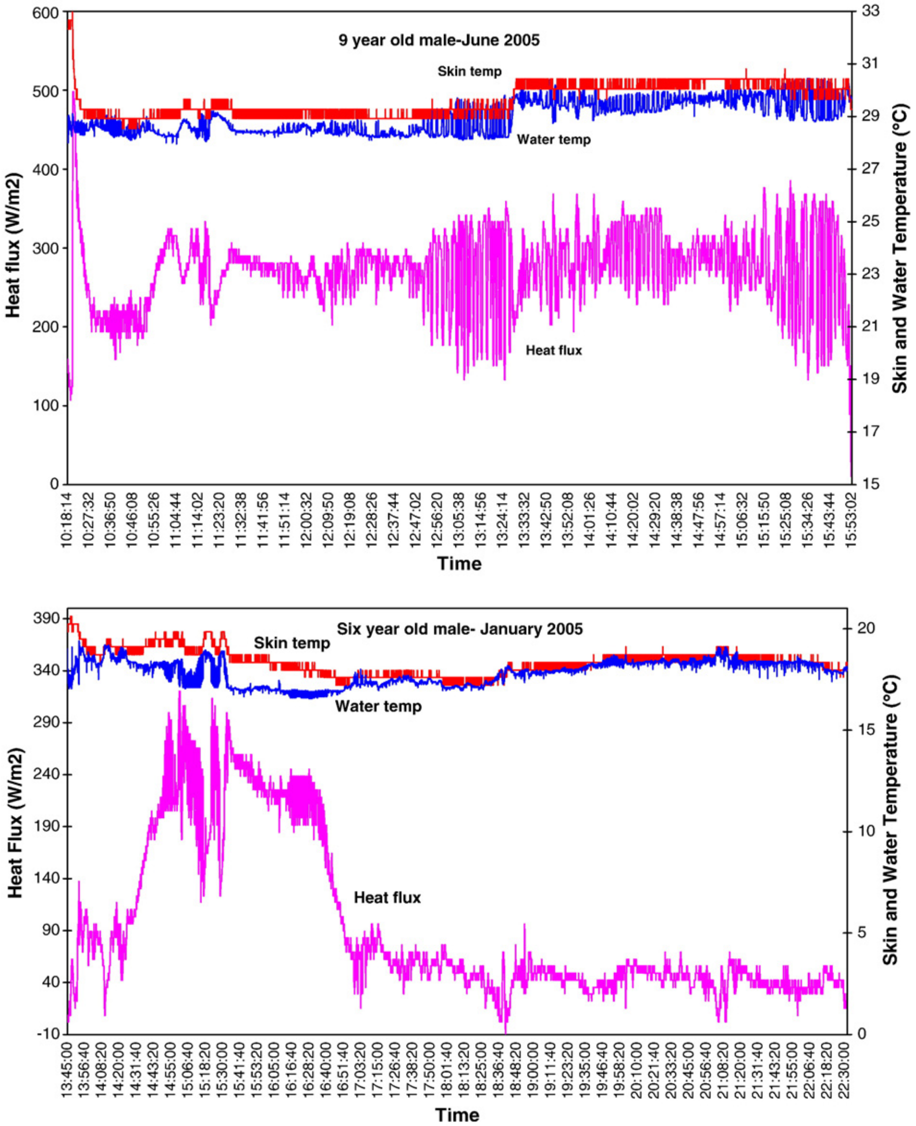

Fig. 6. Records showing seasonal differences in patterns of HF obtained from two bottlenose dolphins in Sarasota Bay, Florida. The upper graph shows a 5 h record obtained from a 9-year old male during summer when water temperatures approached 30 °C. HF is variable but remains around 250 W/m^2. The lower trace shows an eight hr record from a six-year old male obtained during January when water temperatures were around 17 °C. The animal shows characteristic variation in HF but note that HF falls off and remains at very low levels after 17:00; a pattern that was observed in the majority of winter deployments.

Our saddle was designed to let water flow freely across the dorsal fin and around the HF disk as the animal moved through the water column. This design feature minimized any insulative effects of the package and allowed both conductive and convective components of heat flow to be assessed. The less-invasive suction-cup design was deployed without difficulty on a wide size range of bottlenose dolphins and could be easily adapted to fit other species with different dorsal fin shapes. The package detached remotely, which eliminated the need to re-capture animals but surveillance was required during deployment to ensure recovery. The pin-mounted configuration was a more invasive approach that allowed longer deployment times. The fact that it was successfully used on a smaller dolphin species suggests that it could be adaptable to many species providing they have a sufficiently large dorsal fin and could be safely captured. The design, as presented here, could also be adapted to accommodate other similar-sized data

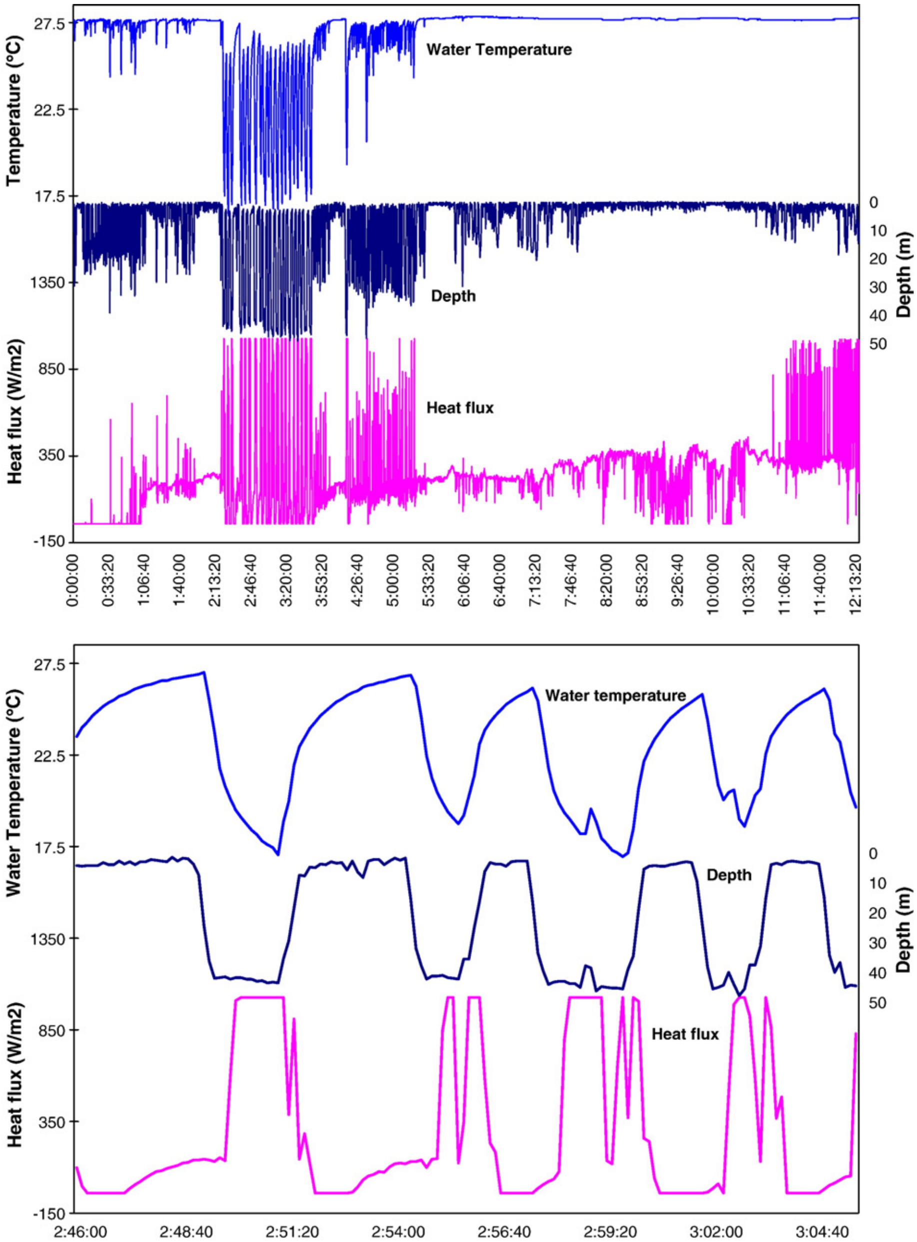

Fig. 7. A 12-hour record of heat flux (HF), diving behaviour and water temperature obtained from a mature male spotted dolphin in the eastern tropical Pacific Ocean. By incorporating a time–depth recorder we were able to examine patterns of heat flux in relation to diving and swimming behaviours. The lower part of the figure shows an expanded 20 min section showing that as the dolphin dives it encounters cooler water and shows a corresponding increase in HF. HF records are clipped because amplified voltages from the HF disks exceeded both the minimum (0 V) and maximum (2.5 V) resolution capabilities of the HOBO logger.

sensors and loggers, depending in the specific experimental questions being addressed. By having a single self-contained unit that incorporated multiple sensors and all the required electronics of the logger, we believe the risk to the animals was reduced and potential package retention was enhanced.

4.1. Dorsal fin as heat source

In addition to being a logical place to attach external devices (Irvine et al., 1982; Scott et al., 1990), the dorsal fin of dolphins has been described as a thermal control surface (reviewed by Pabst et al., 1999), meaning that both its temperature and heat loss capacity can be regulated by the dolphin depending on the animal's thermoregulatory needs (Noren et al., 1999; Meagher et al., 2002). Thus, any measured changes in HF can provide insight into the thermal status of an individual (Meagher et al., 2002). Our results support previous studies (Noren et al., 1999; Williams et al., 1999) that showed that heat flux and temperature recorded at the dorsal fin were variable and changed with behavioural state (see below and Fig. 7). Due to the complexities in the anatomical and physiological mechanisms that control heat loss in dolphins (Pabst et al., 1999) it would be incorrect to assume that HF, as measured at the dorsal fin, could be directly used in a calculation of whole body heat loss. However, we have shown that this new device can effectively record dynamic patterns in heat loss in free-swimming dolphins.

4.2. Assessment of data collection capabilities

We deployed the device in both pelagic and coastal habitats and in water temperatures that ranged from 16 to 30 °C. The package collected data to depths of 71 m and at relative speeds up to 5 m/s. Both devices performed well over this wide range of environmental conditions. Preliminary examination of the data revealed that heat loss is highly variable and changes throughout a deployment. For example, Fig. 7 shows a detailed portion of the record obtained from a spotted dolphin in the ETP. Here we see dynamic variation in T_w and HF as the animal goes through a series of deep (50 m) dives through the thermocline. Heat flux, as measured at the dorsal fin, dramatically increased as the animal dove and T_w decreased. As the animal returned to the surface and T_w increased, HF decreased. This pattern repeated with each subsequent dive. In Fig. 6 we see two records from male bottlenose dolphins, one obtained during winter and one obtained during summer. In the summer, HF stayed relatively constant throughout the deployment, while in winter HF dropped off to very low levels 3 h after the animal was released. Although still pending further analysis, we hypothesize that this reduction in HF reflects vascular adjustments being made by the dolphin to minimize heat loss as it moves through cooler water in winter [this trend was seen in five of the six longer (>30 min) wintertime deployments on bottlenose dolphins]. Both these examples illustrate the utility of the new device as it allows the dynamic nature of heat flow in dolphins to be recorded.

Retention times varied with the suction-cup version of the thermal data logger (Fig. 4). Of the 55 deployments, 67% remained on the dolphins for at least 30 min and 18% for at least 4 h. The failure rate (i.e., the total number of deployments shorter than our experimental cut-off of 30 min) was dictated by the individual behaviour of the tagged dolphins and the shapes of their dorsal fins, which varied in the degree of concavity or convexity. Dolphins could dislodge the thermal package either by engaging in bottom rubbing, breaching or by quickly changing their trajectory through the water. Rather than view the number of dislodged packs as a design short-coming we agree with Johnson and Tyack (2003) and interpret it as a positive design feature that allows animals that are so motivated to easily remove the package.

The same could not be said for the long-term design, which was surgically pinned directly to the dorsal fin. In the ETP experiments, the more invasive tag attachment was chosen to ensure longer tag retention times. The goal of this work was to measure a dolphin's thermal response to chase and re-capture. In this case the choice of the invasive attachment was made because of the potential value of the experimental data in informing conservation and management. Our data set using the long-term version is limited to two individuals but both provided high-quality data records. This more invasive approach may have more specialized application such as when access to animals is logistically complex (as in the ETP) or when the research question requires longer-term data. Future applications will have to weigh the costs and benefits of the short- and long-term designs in the context of animal access and behaviour, ease of capture, and the importance and relevance of the questions being addressed.

4.3. Biases and design improvements

Heat flux measurements tend to be negatively biased because of the localized insulation effects of the HF disk (Ducharme et al., 1990; Frim and Duchaarme, 1993). Using an innovative approach, Willis and Horning (2005) calculated the positive correction factor of their pinniped heat flux logger as being 3.42. We used a similar approach to evaluate the errors associated with our system. While the details of this correction procedure will be presented elsewhere (E. Meagher UNCW, unpublished data), our seasonally adjusted correction factors were 1.37 in winter and 1.76 in summer. In this study we present corrected values for all our HF records.

We designed our loggers to minimize biases that would be introduced by the insulative effects of the saddles but these effects were likely not negligible. The short-term logger used suction cups for attachment which themselves covered up about 50 cm^2 or about 10% of the total surface area of an average bottlenose dolphin dorsal fin (males = 620 cm^2, females = 465 cm^2, Tolley et al., 1995). The suction cups raised the rest of the saddle off the surface of the dorsal fin which allowed water to flow around the suction cups and over the exposed skin surface. There was also a hole cut through the side of the plastic housing that supported the HF transducer (Fig. 1) that allowed a continuous flow of water across the back side of the HF transducer. The long-term logger also sat above the surface of the dorsal fin because of the 3.0-mm-thick foam spacers that were placed between the saddle and the skin on each side of the two pins. These small 2-cm-diameter inserts covered an area of approximately 12 cm^2 (i.e. $4 \times \pi$ 1.0 cm ^{2}) which we estimated covered less than 3% of the total surface area of the average spotted dolphin dorsal fin (400 cm^2, E. Edwards, National Marine Fisheries Service, unpublished data). Similarly, the long-term logger also had a hole through the saddle to allow water flow over the HF transducer (Fig. 1). Unfortunately it is impossible to collect HF data without introducing some errors caused by insulative effects. We took steps to minimize these effects by keeping the packages as small as possible while maintaining good water flow.

We chose the 4-channel HOBO because it was small and lightweight, easy to use with the manufacturer's software (HOBO Boxcar pro 4.0), provided sufficient memory (32K) and had an adequate sampling resolution (10 mV). Since the sensors were capable of sampling at a higher resolution, upgrading this component would improve the overall data collection capabilities of the thermal package.

When the amplification circuit was first designed, a 100 mV positively biased offset was incorporated, so minor voltage drift below zero could be accounted for. During some of the deployments it was evident that dolphins were actually cooler than the water, resulting in reversed heat flow (see Fig. 7). Since the HOBO 4-channel was not capable of recording negative voltages, only reversed heat flow that produced voltages less than 100 mV could be accounted for (approx. −42 W/m^2). Future deployments should make adjustments for this limitation by either using a data logger that can read negative voltages or by setting the offset to a higher value.

5. Conclusions

We have presented a new technique to record thermal data remotely from free-swimming dolphins. The design has undergone extensive field testing and has performed well under a variety of experimental conditions. The new thermal data logger improves our ability to collect heat flow data because it records both conductive and convective sources, allows the experimental subjects to move about in and react thermally to their natural habitat, and, in the case of the short-term package, removes the need for further human intervention once the tags have been attached. By simultaneously collecting data on diving and activity behaviour it will now be possible to measure how dolphins respond thermally to dynamic environmental conditions such as changes in water temperature with depth and under different behavioural states.

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References

Davis, R.W., Worthy, G.A.J., Würsig, B., Lynn, S.K., Townsend, F.I., 1996. Diving behavior and at-sea movements of an Atlantic spotted dolphin in the Gulf of Mexico. Mar. Mamm. Sci. 12, 569–581.

Doidge, D.W., 1990. Integumentary heat loss and blubber distribution in the beluga, *Delphinapterus leucas*, with comparisons to the narwhal, *Monodon monoceros*. In: Smith, T.G., St. Aubin, D.J., Geraci, J.R. (Eds.), Advances in Research on the Beluga Whale, *Delphinapterus leucas*. Can. Bull. Fish. Aquat. Sci., vol. 224, pp. 129–140.

Ducharme, M.B., Frim, J., Tikuisis, P., 1990. Errors in heat flux measurements due to thermal resistance of heat flux disks. J. Appl. Physiol. 69, 776–784.

Dunkin, R.C., McLellan, W.A., Blum, J.E., Pabst, D.A., 2005. The ontogenetic changes in the thermal properties of blubber from Atlantic bottlenose dolphin *Tursiops truncatus*. J. Exp. Biol. 208, 1469–1480.

Elsner, R., 1999. Living in water: solutions to physiological problems. In: Reynolds III, J.E., Rommel, S.A. (Eds.), Biology of Marine Mammals. Smithsonian Press, Washington D.C, pp. 73–116.

Frim, J., Duchaarme, M.B., 1993. Heat flux transducer measurement error: a simplified view. J. Appl. Physiol. 74, 2040–2044.

Forney, K.A, St. Aubin, D.J., Chivers, S.J., 2002. Chase encirclement stress studies on dolphins involved in the eastern tropical Pacific Ocean purse–seine operations in 2001. Admin. Report LJ-02-32. Southwest Fisheries Science Center, La Jolla CA. 26 pp.

Gerrodette, T., Forcada, J., 2005. Non-recovery of two spotted and spinner dolphin populations in the eastern tropical Pacific Ocean. Mar. Ecol. Prog. Ser. 291, 1–21.

Hampton, I.F.G., Whittow, G.C., 1976. Body temperature and heat exchange in the Hawaiian spinner dolphin, *Stenella longirostris*. Comp. Biochem. Physiol. 55A, 195–197.

Hampton, I.F.G., Whittow, G.C., Szekerczes, J., Rutherford, S., 1971. Heat transfer and body temperature in the Atlantic bottlenose dolphin, *Tursiops truncatus*. Int. J. Biometeorol. 15, 247–253.

Heath, M.E., Ridgway, S.H., 1999. How dolphins use their blubber to avoid heat stress during encounters with warm water. Am. J. Physiol. 45, 1188–1194.

Irvine, A.B., Wells, R.S., Scott, M.D., 1982. An evaluation of techniques for tagging small odontocete cetaceans. Fish. Bull. 80, 135–143.

Johnson, M.P., Tyack, P.L., 2003. A digital acoustic recording tag for measuring the response of wild marine mammals to sound. IEEE J. Oceanic Eng. 28, 3–12.

Koopman, H.N., 1998. Topographical distribution of the blubber of harbor porpoises (*Phocoena phocoena*). J. Mammal. 79, 260–270.

Lander, M.E., Westgate, A.J., Bonde, R.K., Murray, M.J., 2001. Tagging and tracking, In: Dierauf, L., Gulland, F. (Eds.), CRC Handbook of Marine Mammal Medicine, 2nd edition. Chemical Rubber Company Press, Boca Raton, pp. 851–880.

McGinnis, S.M., Whittow, G.C., Ohata, C.A., Huber, H., 1972. Body heat dissipation and conservation in two species of dolphins. Comp. Biochem. Physiol. 43A, 417–423.

McNab, B.K., 2002. The Physiological Ecology of Vertebrates: A View from Energetics. Cornell University Press, Ithaca. 576 pp.

Meagher, E.M., McLellan, W.A., Westgate, A.J., Wells, R.S., Frierson, D., Pabst, D.A., 2002. Respiration, heart rate and heat flux across the dorsal fin in bottlenose dolphins, *Tursiops truncatus*. J. Exp. Biol. 205, 3475–3486.

National Research Council, 1992. Dolphins and the Tuna Industry. National Academy Press, Washington D.C. 176 pp.

Noren, D.P., Williams, T.M., Berry, P., Butler, E., 1999. Thermoregulation during swimming and diving in bottlenose dolphins, *Tursiops truncatus*. J. Comp. Physiol. B 169, 93–99.

Norman, S.A., Hobbs, R.C., Foster, J., Schroeder, J.P., Townsend, F.I., 2004. A review of animal and human health concerns during capture–release, handling and tagging of odontocetes. J. Cetacean Res. Manag. 6, 53–62.

Nowacek, D.P., Tyack, P.L., Wells, R.S., Johnson, M.P., 1998. An onboard acoustic data logger to record biosonar of free-ranging bottlenose dolphins. J. Acoust. Soc. Am. 103, 2908–2909.

Pabst, D.A., Rommel, S.A., McLellan, W.A., 1999. Functional morphology of marine mammals. In: Reynolds III, J.E., Rommel, S.A. (Eds.), Biology of Marine Mammals. Smithsonian Press, Washington D.C., pp. 15–72.

Parry, D.A., 1949. The structure of whale blubber, and a discussion of its thermal properties. Q. J. Microc. Sci. 90, 13–25.

Read, A.J., Westgate, A.J., 1997. Monitoring the movements of harbour porpoises *Phocoena phocoena* using satellite telemetry. Mar. Biol. 130, 315–322.

Reeves, R.R., Stewart, B.S., Clapham, P.J., Powell, J.A., Folkens, P.A., 2002. Guide to Marine Mammals of the world. Knopf, New York. 527 pp.

Rommel, S.A., Pabst, D.A., McLellan, W.A., Mead, J.G., Potter, C.W., 1992. Anatomical evidence for a countercurrent heat exchanger associated with dolphin testes. Anat. Rec. 232, 150–156.

Rommel, S.A., Pabst, D.A., McLellan, W.A., 1993. Functional morphology of the vascular plexuses associated with the cetacean uterus. Anat. Rec. 237, 538–546.

Rommel, S.A., Pabst, D.A., McLellan, W.A., Williams, T.M., Friedl, W.A., 1994. Temperature regulation of the testes of the bottlenose dolphin (*Tursiops truncatus*): evidence from colonic temperatures. J. Comp. Physiol. B 164, 130–134.

Schmidt-Nielsen, K., 1997. Animal Physiology: Adaptation and Environment, 5th ed. Cambridge University Press, Cambridge. 612 pp.

Scholander, P.F., Schevill, W.E., 1955. Counter-current vascular heat exchange in the fins of whales. J. Appl. Physiol. 8, 279–282.

Scott, M.D., Wells, R.S., Irvine, A.B., Mate, B.R., 1990. Tagging and marking studies on small cetaceans. In: Leatherwood, S., Reeves, R.R. (Eds.), The Bottlenose Dolphin. Academic Press, San Diego, pp. 489–514.

Shippee, S.F., Townsend, F.I., Deckert, F.L., Gates, D.L., 1995. A tracking and monitoring system for free swimming dolphins using a Trac-Pac dorsal fin tag. Abstract Published in Proceedings of the 23rd Annual IMATA Conference, November 1995, Las Vegas, NV. International Marine Animal Trainers Association, Chicago.

Tolley, K.A., Read, A.J., Wells, R.S., Urian, K.W., Scott, M.D., Irvine, A.B., Hohn, A.A., 1995. Sexual dimorphism in wild bottlenose dolphins (*Tursiops truncatus*) from Sarasota, Florida. J. Mammal. 76, 1190–1198.

Wells, R.S., 1991. The role of long-term study in understanding the social structure of a bottlenose dolphin community. In: Pryor, K., Norris, K.S. (Eds.), Dolphin Societies: Discoveries and Puzzles. University of California Press, Berkeley, pp. 199–225.

Wells, R.S., Scott, M.D., Irvine, A.B., 1987. The social structure of free-ranging bottlenose dolphins. In: Genoways, H. (Ed.), Current Mammalogy, vol. 1, pp. 247–305.

Wells, R.S., Rhinehart, H.L., Hansen, L.J., Sweeney, J.C., Townsend, F.I., Stone, R., Casper, D., Scott, M.D., Hohn, A.A., Rowles, T.K., 2004. Bottlenose dolphins as marine ecosystem sentinels: developing a health monitoring system. EcoHealth 1, 246–254.

Westgate, A.J., Read, A.J., Berggren, P., Koopman, H.N., Gaskin, D.E., 1995. Diving behaviour of harbour porpoises, *Phocoena phocoena*. Can. J. Fish. Aquat. Sci. 52, 1064–1073.

Williams, T.M., Noren, D., Berry, P., Estes, J.A., Allison, C., Kirtland, J., 1999. The diving physiology of bottlenose dolphins (*Tursiops truncatus*). J. Exp. Biol. 202, 2763–2769.

Willis, K., Horning, M., 2005. A novel approach to measuring heat flux in swimming animals. J. Exp. Mar. Biol. Ecol. 315, 147–162.

Worthy, G.A.J., Edwards, E.F., 1990. Morphometric and biochemical factors affecting heat loss in a small temperate cetacean (*Phocoena phocoena*) and a small tropical cetacean (*Stenella attenuata*). Physiol. Zool. 63, 432–442.